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The impact of a short-term carbon payment scheme on forest management

Artti Juutinen[a,b,*], Anssi Ahtikoski[a], Mika Lehtonen[c], Raisa Mäkipää[d], Markku Ollikainen[e]

[a] Natural Resources Institute Finland, P.O. Box 413, University of Oulu, FI-90014, Finland
[b] Department of Economics, P.O. Box 4600, University of Oulu, 90014 FI, Finland
[c] Natural Resources Institute Finland, P.O. Box 18, Vantaa FI-01371, Finland
[d] Natural Resources Institute Finland, Latokartanonkaari 9, FI-00790 Helsinki, Finland
[e] Department of Economics and Management, P.O. Box 27, FI-00014, University of Helsinki, Finland

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ABSTRACT

We examine the feasibility and impacts of a short-term carbon payment mechanism on forest management in boreal forests. Unlike under long-term carbon sequestration commitments over a rotation period, landowners are allowed in this scheme to sell temporal carbon credits based on stored carbon for one year and reissue them annually. Using numeric optimization we show that the short-term carbon payment mechanism has a profound effect on the timing and intensity of thinning, and the optimal rotation length showing up in higher timber yield and improved profitability. A comparison of the case where all carbon or only additional carbon above that in timber management benchmark is accounted for by the short-term payment scheme shows that the optimal forest management remains roughly the same. However, the increase in the profitability of forestry introduced by carbon credits is relatively small, if only additional carbon is credited. Hence the short-term mechanism may be feasible only under high carbon prices and it would most likely increase rotation length of mature stands with additionality requirement in boreal forests.

1. Introduction

Climate change is perhaps the greatest challenge the humankind faces. Article 2 of the Paris Climate Agreement 2015 sets the global climate goal, which requires: “Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.” Both temperature targets are demanding, and require a very rapid reduction of GHG emissions globally. Rapid reduction of emissions is not enough, though. Carbon sinks and other means of carbon removal are needed to complement emission reduction efforts. In fact, by 2070 developed countries should be carbon negative.

World forests can efficiently mitigate climate change by sequestering carbon from the atmosphere. Forests capture atmospheric CO2 through photosynthesis and store it as carbon in biomass and soil. The carbon may stay in the forest biomass and soil or in wood products for some time, but the stock is temporal, since all carbon fixed by the photosynthesis is eventually released back to atmosphere when dead trees, litter, cutting residues and wood products decompose (Liski et al., 2001). Therefore, the balancing the size of carbon stock against the rate of carbon uptake is an important issue for forest management. Both afforestation and climate-smart forest management provide large mitigation potential. No wonder that majority of the countries included forests in their Intended Nationally Determined Contributions under the Paris Climate Agreement in 2015 (http://unfccc.int/focus/indc_portal/items/8766.php). As the first country in the world, New Zealand included forestry in country's emissions trading scheme. Forest landowners are allowed to earn carbon credits by sequestering carbon in their forests, but should they harvest or deforest their forests, a payback of credit is required (Adams and Turner, 2012). The EU has decided to include land use, land use change and forestry (the so-called LULUCF sector) in the EU climate policy by 2020, giving a higher role for forestry in climate policy (Nabuurs et al., 2015). However, forest owners are not compensated for forest carbon sequestration.

Currently, the absence of climate incentives for forestry represents an important missed opportunity that could have remarkable contribution to mitigation of climate change (Nabuurs et al., 2015; Moen et al., 2014). Proposed Pigouvian policies favor subsidizing carbon sequestration and taxing carbon release (van Kooten et al., 1995). As an additional source of revenue, a subsidy or a related compensation scheme presumably changes forest management in a way that results in a higher rate of tree growth or longer rotations.

* Corresponding author at: Natural Resources Institute Finland, P.O. Box 413, University of Oulu, FI-90014, Finland.
E-mail addresses: artti.juutinen@luke.fi (A. Juutinen), anssi.ahtikoski@luke.fi (A. Ahtikoski), mika.lehtonen@luke.fi (M. Lehtonen), raisa.makipaa@luke.fi (R. Mäkipää), markku.ollikainen@helsinki.fi (M. Ollikainen).

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Several studies have analyzed the effects of the inclusion of carbon sequestration subsidies on forest management. Most studies have focused mainly on the rotation length but also thinnings has been considered (van Kooten et al., 1995; Hoen and Solberg, 1997; Pohjola and Valsta, 2007; Pukkala, 2011; Asente and Armstrong, 2012). Recently, the role of initial density was incorporated in the analysis (Goetz et al., 2010; Niinimäki et al., 2013; Pihlainen et al., 2014). All papers have postulated a subsidy/tax mechanism, which represents a long-term purchase approach, originally suggested by van Kooten et al. (1995).

In this commonly applied long-term scheme landowners receive a subsidy for carbon uptake, and pay a tax when carbon is released via harvesting. But is it actually the best alternative for forest management? For rapidly growing trees with short rotation ages perhaps, but not necessarily for the slowly growing boreal forests, which have increasingly important role for forest products. Socio-economic studies suggest that landowners in boreal areas may not be willing to make long-term commitments for providing ecosystem services in their forests (Horne, 2006; Markowski-Lindsay et al., 2011).

In this paper we introduce a short-term subsidy scheme and examine how well it suits to boreal forests involving long rotation periods. Previously the short-term subsidy scheme has been applied to afforestation and carbon sequestration within REDD+ mechanism (Galinato and Uchida, 2010, 2011; Olschewski and Benitez, 2010; Galinato et al., 2013; Cacho et al., 2013). It is important to investigate, however, how the short-term carbon policy developed merely for plantation forests in tropical countries performs when applied to management of existing semi-natural forests that are gaining an increased importance in the EU climate policy (Nabuurs et al., 2015). In the short-term rental subsidy scheme landowners are allowed to sell temporal carbon credits based on the stored carbon for one to ten years, for example and reissue them after expiration. Thus landowners have a possibility to opt out of the carbon payment mechanism and change the management schedule after the expiry period without any penalty. To our knowledge, the impacts of short-term incentive mechanism on the management of commercial boreal forests have not been previously studied. Lintunen et al. (2016) compared analytically the equivalency of rental and purchase carbon policies, but they did not examined how the short-term policy impacts on optimal forest management and what is the potential of short-term rental policy in boreal forest.

We impose the short-term rental compensation scheme and ask how the landowners will manage their forests when they receive harvest revenue and income from carbon sequestration. We contribute to the literature several ways. First, instead of postulating a steady-state forestry, we allow for alternative initial states of stands when climate incentives are introduced. To create a comprehensive description of forest management, landowners are assumed to optimize over a wide range of management variables including rotation length and the number, timing, type, and intensity of thinning as well as precommercial thinning. Previous optimization studies have focused on forest stands representing different fertility classes, but have not considered variation between stands characteristics within the fertility classes (e.g., Niinimäki et al., 2013; Pihlainen et al., 2014).

Second, we also examine the role of additionality. In many practical implementations of forest-carbon policies (UNFCCC, 2011; CEPA, 2014), the payments are restricted to actions or services that are indeed additional in the sense that they have not already been carried out, or would have been carried out in the absence of the contract. Regarding afforestation projects the additionality is an obvious outcome, but that is not the case when management of existing forests is considered. In our approach the carbon credits are calculated as a difference in stored carbon between the baseline timber management and the joint management similarly as in Latta et al. (2011) and Man et al. (2015).

Third, we also focus on the role of transaction costs of the short-term payment mechanism. High transaction costs may be an obstacle to the system, in which case the prevailing market carbon prices may not provide enough incentive for adoption (Cacho et al., 2013). Given that the short-term rental mechanism is not yet applied in the EU climate policy, the transaction costs are unknown. Therefore, we assess the feasibility of the mechanism by estimating the maximum transaction cost level at which forest owner's net benefit of participation to the carbon trade is not negative.

2. Materials and methods

2.1. Carbon policy

Consider now the following voluntary climate policy targeting forest management. The landowners are allowed to produce short-term carbon credits with a year as the commitment period and sell them in the carbon market. The credited and certified carbon stock is defined as a difference in annual carbon stocks between the joint timber and carbon management and the baseline timber management, and measured in tonnes of carbon dioxide. The credit is temporary and expires at the end of the commitment period following the year during which it was issued. Then, new credits can be issued annually in any subsequent year during the rotation period as long as the stand is not clear-cut.[1] When the stand is clear-cut, the carbon stock is zero and there are no credits to sell.

The short-term credits mechanism differs fundamentally from the conventional long-term payment mechanism in which landowners sell permanent credits. A permanent carbon credit scheme is based on a change of carbon storage between two sequential periods. It will not expire but the landowner has to pay a penalty (tax) when carbon storage is reduced, because harvesting makes carbon sequestration negative. In contrast, the short-term mechanism gives landowners a possibility to opt out of the carbon payment mechanism and change the management regime after one year expiry period without any penalty. Naturally, the difference shows up in the prices of carbon, too. Under the short-term mechanism, prices for temporal credits, derived from those of permanent credits, are much smaller than under permanent payment mechanism.

We next formalize the short-term payment mechanism and the benchmark. The absence of carbon policies defines the baseline management, where the landowner maximizes only the net present value (NPV) of harvest revenue by deciding number, timing, intensity, and type of thinnings as well as rotation length. The management actions impact forest growth and biomass yield, and therefore, they also determine harvest volumes and net harvest revenues. Under the carbon payment policy, they are used to control the carbon storage in the stand and the carbon payments the landowner receives along with the net harvest revenues. Naturally, forest growth depends also on many stand characteristic, such as soil fertility and initial state of the stand.

At a general level, the landowner's optimization problem can be presented as a discrete-time system of state and control variables (cf., Cao et al., 2006; Tahvonen et al., 2013). Let Z_{t_i} describe stand state before the i th potential harvest at stand age t_i, $i = , 0, \ldots, T$. We use t_0 to denote the initial stand age and the final harvest (clear-cutting) occurs at stand age t_T. The initial stand state Z_{t_0} is given. In the empirical modeling the stand state includes multiple variables, but here it simply denotes biomass volume of standing trees (m^3). Let k ($k = 1, \ldots, K$) denote different timber assortments of the trees in the given stand including, for example, pulpwood and saw logs. Stumpage price (€/m^3) for a timber assortment k is denoted by p_k. Let the real interest rate be r. The harvest volumes (m^3) for each timber assortment k and harvest i are denoted by h_{ki}. The volume of precommercial thinning is denoted by $\hat{h}_i$ and the associated unit cost by s. Obviously the precommercial thinning

[1] Choosing a year as the contract period is naturally not the only option for short-term incentives, for instance, a five year long period would be equally feasible choice (see Galinato et al., 2013). The one-year period was chosen in this paper for simplicity to facilitate the numeric optimizations, because the focus was on contract design question rather than in the specific details of a policy.

is conducted before the first commercial thinning. The harvest volumes depend on stand state and harvest intensity and timing. The proportion of harvested volume of total available volume in harvest i is denoted by g_i and $\hat{g}_i$ for thinning (and final harvest) and percommercial thinning, respectively. The harvest volumes depend also on the (exogenous) site productivity denoted by θ. The control variables include the timing of harvest (t_i, $i = 0, \ldots, T$), the number of harvest (T), and the intensity of harvests (g_i and $\hat{g}_i$). Using this notation, the net present value of harvest revenue in the benchmark (NPV^b) can be expressed as,

$$\max NPV^b = \sum_{i=0}^{T} \left\{ \sum_{k=1}^{K} p_k h_{ki}(Z_{t_i}, g_i, \theta) - s\hat{h}_i(Z_{t_i}, \hat{g}_i, \theta) \right\} (1+r)^{-(t_i - t_0)} - LEV\,(1+r)^{-(t_T - t_0)} \quad (1)$$

subject to the equation $Z_{t_{i+1}} = f(Z_{t_i}, g_i, \hat{g}_i, \theta)$ and some other technical requirements that are not shown here to simplify the presentation.

The NPV^b consists of two components in Eq. (1).[2] The first component represents the ongoing rotation. The terms in the first component in parenthesis denote the net harvest revenue from thinning and final harvest over the silvicultural costs caused by precommercial thinning. The second component is the land expectation value (LEV), which takes into account the harvest revenues from all future rotations. Note that regeneration costs are not included in the NPV^b as initial stands are considered.[3]

Turning to climate policies, let the value of stored carbon (tCO_2) at stand age t_i under the baseline management be c_i^b and under joint management by c_i^j. The carbon price (€/tCO_2) is p_c. The landowner chooses now stand management so as to maximize the sum of net present value of harvest revenue and income from selling carbon credits. The net present value of the joint production (NPV^j) is formally:

$$\max NPV^j = \sum_{i=0}^{\overline{T}} \left\{ \sum_{k=1}^{K} p_k h_{ki}(Z_{t_i}, \overline{g}_i, \theta) - s\hat{h}_i(Z_{t_i}, \hat{\overline{g}}_i, \theta) + p_c\left(c_i^j(Z_{t_i}, \overline{g}_i, \hat{\overline{g}}_i, \theta) - c_i^b(Z_{t_i}, g_i, \hat{g}_i, \theta)\right) \right\} (1+r)^{-(t_i - t_0)} - LEV\,(1+r)^{-(t_{\overline{T}} - t_0)} \quad (2)$$

subject to $Z_{t_{i+1}} = f(Z_{t_i}, \overline{g}_i, \hat{\overline{g}}_i, \theta)$. $\overline{T}$ denotes the number of harvests under the carbon payment scheme. Respectively, $\overline{g}_i$ and $\hat{\overline{g}}_i$ denote the harvest intensity. The difference to previous equation lies in the new term indicating net income from carbon credits. The additionality requirement is accounted for in Eq. (2) by calculating the difference in stored carbon between the baseline and the joint managements ($c_i^j - c_i^b$).

This far we have not devoted much attention to the carbon market, which may be a mandatory or voluntary market, for instance, targeting fossil industries. Potential buyers of forest carbon credits in carbon markets are assumed to be indifferent between buying a permanent credit today and buying a non-permanent credit today and replacing it by a permanent one when the initial credit expires (Olschewski and Benitez, 2010). Accordingly the price for temporal carbon credits is valid for one year and calculated using the price for a permanent unit p_∞ and the interest rate as $p_c = p_\infty\left(1 - \frac{1}{1+r}\right)$. In what follows we assume that carbon credit is zero if $c_i^b > c_i^j$, that is, there are no penalties in the case less carbon is stored in the joint production at stand age t_i than in the timber production. For the time periods exceeding t_T we determine c_i^b according the new rotation followed after clear-cutting in the baseline timber management. Finally, we assume that there are no transaction costs among sellers or buyers.

2.2. Forest simulation and optimization

We simulated stand growth and forestry operations using the Motti simulator developed by the Natural Resources Institute Finland. The Motti software is designed to simulate stand development under alternative management regimes in Finnish growth conditions to primarily assess growth and yield (Hynynen et al., 2002; Matala et al., 2003; Salminen et al., 2005), but also financial performance of forestry (Hynynen et al., 2005; Hynynen et al., 2014). The Motti is an empirical-statistical growth and yield model that includes the most recent descriptions of stand dynamics (Hynynen et al., 2002, 2005, 2014). The models used in the Motti are based on extensive empirical data from permanent field sites and forest inventory plots covering also stand structures exceeding common rotation lengths. The Motti simulator has been widely applied at stand-level analysis in earlier studies (Hynynen et al., 2005; Ahtikoski et al., 2012), and the stand projections of the Motti have been tested against measured observations indicating that the projections are applicable (Mäkinen et al., 2005; Huuskonen, 2008). The models of Motti are based on empirical material from forests managed mainly according to prevailing regulations. Thus, applying Motti outside these extents would cause some uncertainty in model predictions. In this study, the Motti was applied within the data range (see Supplementary material for more details about the Motti).

To find optimal management regimes we used a specific Motti version incorporated with optimization package based on PIKAIA algorithm (Ahtikoski et al., 2012, 2013), which utilizes a genetic algorithm (Charbonneau and Knapp, 1995; Metcalfe and Charbonneau, 2003). The objective of optimization was maximization of net present value under the benchmark timber production (Eq. (1)) and the joint timber and carbon production (Eq. (2)). The parameter space (i.e., the entity within the optimal solutions are searched for) in this study was complex, including 15 decision variables that were used to control the stand dynamics and the associated net harvest revenues and carbon payments. The parameters were 1) the timing of the precommercial thinning 2) intensity of the precommercial thinning 3) timing of the first thinning and 4) intensity of the first thinning, 5) the timing and 6) intensity of the subsequent thinnings, 7–10) the relative diameter distribution of the remaining stock after the first thinning, 11–14) the relative diameter distribution of the remaining stock after the following thinnings, and 15) timing of the clear-cutting.

2.3. Carbon storage

The carbon stock associated with each stand-level optimum was assessed by calculating the amount of carbon in above-ground living biomass (Hynynen et al., 2014). The carbon compartments included into this study were: stem, foliage, living and dead branches and bark (cf. Cao et al., 2010). Both the soil carbon and carbon sequestrated in dead wood (i.e. dead trees created by natural mortality and harvests and their mass loss due to decomposition) were excluded from the analysis. The share of carbon in dry weight of biomass was assumed to be 0.5 (IPCC, 2006), and the amount of carbon was converted into carbon dioxide (CO_2) by multiplying it with 3.67 which is the ratio between atomic weights of carbon dioxide and carbon (44/12). We considered only carbon content of the living tree biomass above ground, as the volume of this part of biomass is the easiest to verify in carbon payment mechanism. In addition, the biomass of above ground part of the living trees is most directly affected by the forest management activities. Hence we exclude the carbon storages in wood products as well as substitution effects of the use of wood products, which both are driven rather by demand for products than decisions made by a landowner. This issue is better to tackle with policy targeting to

[2] A similar two phase expression of the Faustmann model is used when considering the case of initial stand (Johansson and Löfgren, 1985). Here the expression is applied to take into account that under the short-term payment mechanism a forest owner adapts to the mechanism during the first rotation. The expression used in this study represents a theoretical framework for empirical analysis. The maximization problem does not have an exact analytical solution.

[3] Regarding multiple stands in the simulations, the NPV values are not fully comparable between stands as their initial ages differ. Therefore, the NPV values are presented as bare land values (not including regeneration costs) in the results section, i.e. the NPV values are discounted from t_0 to $t = 0$.

Table 1
Initial characteristics of the examined stands.

Stand number and site type[a]	Main tree species	Biological age, yrs	Number of stems, main tree species	Number of stems, other tree species[b]	Average diameter, cm	Average height, m	Total growing stock, m^3/ha
1 Herb-rich	Norway spruce	10	2500	998 (30%)	5.7	4.1	10.8
2 Herb-rich	Norway spruce	15	3000	700 (71%)	5.7	4.6	17.4
3 Herb-rich	Norway spruce	16	2800	1970 (0%)	6.0	4.6	22.4
4 Mesic soil	Norway spruce	16	2470	1570 (68%)	8.6	6.6	43.1
5 Mesic soil	Norway spruce	13	2200	1490 (66%)	6.0	4.3	12.7
6 Mesic soil	Norway spruce	10	2000	1500 (0%)	3.9	4.0	8.3
7 Mesic soil	Scots pine	11	2110	1060 (100%)	6.0	8.0	25.1
8 Mesic soil	Scots pine	11	1990	1600 (100%)	6.5	5.5	29.7
9 Mesic soil	Scots pine	12	3600	400 (100%)	9.0	6.6	62.9
10 Nutrient-poor	Scots pine	11	2390	600 (100%)	6.3	5.1	19.6
11 Nutrient-poor	Scots pine	11	1790	972 (100%)	6.3	5.3	20.3
12 Nutrient-poor	Scots pine	15	2000	4200 (97%)	5.6	6.3	69.4

[a] Herb-rich refers to *Oxalis-Myrtillus* type; mesic soil to *Myrtillus* type; nutrient-poor to *Vaccinium* type (Tonteri et al., 1990).
[b] The proportion (%) of deciduous trees is shown in the parenthesis.

processing industry (Tahvonen, 1995).

2.4. Data

Conifers are the dominant tree species in managed forest in the boreal zone. In Fennoscandia, Norway spruce (*Picea abies(Karst.)*) is economically the most valuable tree species, but it does not grow well on dry or poor site types, whereas Scots pine (*Pinus sylvestris L.*) is relatively more productive on the less fertile sites. The data for stand-level simulations are obtained from the Finnish Forestry Centre, representing private forests. The data are located in southern Finland, within the Forestry Centre Häme-Uusimaa (ranging app. from. 60°31′ N to 61° 16′N, and from 23°03′ E to 25°14′ E), the length of the growing season fluctuating between 170 and 220 days with threshold 5 °C (Venäläinen et al., 2005). Altogether there are 12 young individual sapling stands in the data set, consisting of two tree species (Norway spruce and Scots pine) on three different site types (fertility classes). The simulated sites represent the most common site fertility classes for these tree species in Finland (Anonymous, 2014). The fertility classes from rich to poor were herb-rich (*Oxalis-Myrtillus*) and mesic (*Myrtillus*) site type for spruce stands, and mesic (*Myrtillus)* and nutrient-poor (*Vaccinium)* site type for pine stands (for Finnish site fertility classification system, see Tonteri et al., 1990). Stand data, i.e. tree characteristics were collected by the Forestry Centre Häme-Uusimaa using ocular field assessment (Anonymous, 2006), and the growing stock (i.e. stem number, average diameter and height) of a sapling stand was described by tree species with the help of circular sample plots (Anonymous, 2003).

Similar, “practical forestry approach” to provide input for simulation research has been applied earlier (Mäkelä et al., 2011).The underlying idea for using sapling stands inventoried by practical field measurements was to capture the natural variation related to particular tree species and site type at juvenile stage of a stand in private forests. Previous studies have typically considered only a single (model) stand for each site type (e.g., Pukkala, 2011 and Pihlainen et al., 2014). The site types, tree species as well as the stand characteristics of the sapling stands are considered to cover the relevant sample of juvenile stands to be included into the emission trading scheme for private forests in case such a scheme takes place in Europe. The 12 stands with relevant stand characteristics are presented in Table 1. The data on stand characteristics were used as an input data for forest growth simulations and optimizations.

2.5. Economic data

Timber is valued at stumpage, and we apply annual time series data on stumpage prices between years 2000 and 2013. The nominal prices are deflated by cost-of-living index (Statistics Finland, 2014) in order to get prices in real terms.[4] The stumpage prices for different timber assortments are: pine saw logs €57.69 m^{-3}, pine pulpwood €16.63 m^{-3}, spruce saw logs €57.37 m^{-3}, spruce pulpwood €23.66 m^{-3}, birch (and other deciduous tree species) saw logs €49.25 m^{-3} and birch pulpwood €16.14 m^{-3}. For the costs of sapling stands we use a unit cost of €30 per hour for machinery, where time-consumption functions are based on the number of removed young trees and average diameter of the removal (Hynynen et al., 2014). The interest rate is assumed to equal 3%. For carbon credits we apply two permanent unit prices: €15 tCO_2^{-1} and €30 tCO_2^{-1}, and they translate to instant prices of €0.443 tCO_2^{-1} and €0.887 tCO_2^{-1}, which can be annually applied in the short-term subsidy scheme, respectively. Ideally, the carbon price should set at the socially optimal level, but the researchers' views are different from the correct price level. Therefore, we use alternative second-best price levels. For comparison, based on meta-analysis of peer-reviewed articles Tol (2005) ends up to roughly 20 euros as the estimate of marginal climate damage. Tol (2011) updates the analysis with new publications and suggests 35 euros. Hence, the carbon prices used in this study reflect well the results of meta-analysis on social cost of carbon.

We use the data to examine, first, a reference case with no carbon policies (i.e., only timber production is aimed), which provides the benchmark to assess carbon policy cases. We then consider the joint production of timber and sequestered carbon assuming all stored carbon during the rotation period is additional and eligible for carbon trading. We then scrutinize how the additionality requirement in carbon policy affects the optimal forest management regime. We represent in the text four representative stands, one from each forest site type, and provide full set of results in Tables A.1 and A.2 in Appendix. Finally, we use the stand level results to assess aggregate level impacts of the short-term carbon payment scheme.

3. Results

3.1. Benchmark: forest management in the absence of climate incentives

The reference case of the timber production with no carbon policies is illustrated in Fig. 1 with dashed lines for the four stands. The optimal rotation age is 70 and 71 years for a herb rich and a mesic Norway spruce stand, respectively, with two thinnings. For Scots pine in mesic and nutrient poor sites the rotation ages are 73 and 91, respectively, with four thinnings.

[4] This approach is in line with the fact that roundwood trade is mostly done using standing sales in Finland. Forest industry prefers standing sales to delivery sales due to logistical advances which pushes roadside prices downwards. Consequently, use of roadside prices and harvest costs in the optimization would have underestimated the profitability of forestry.

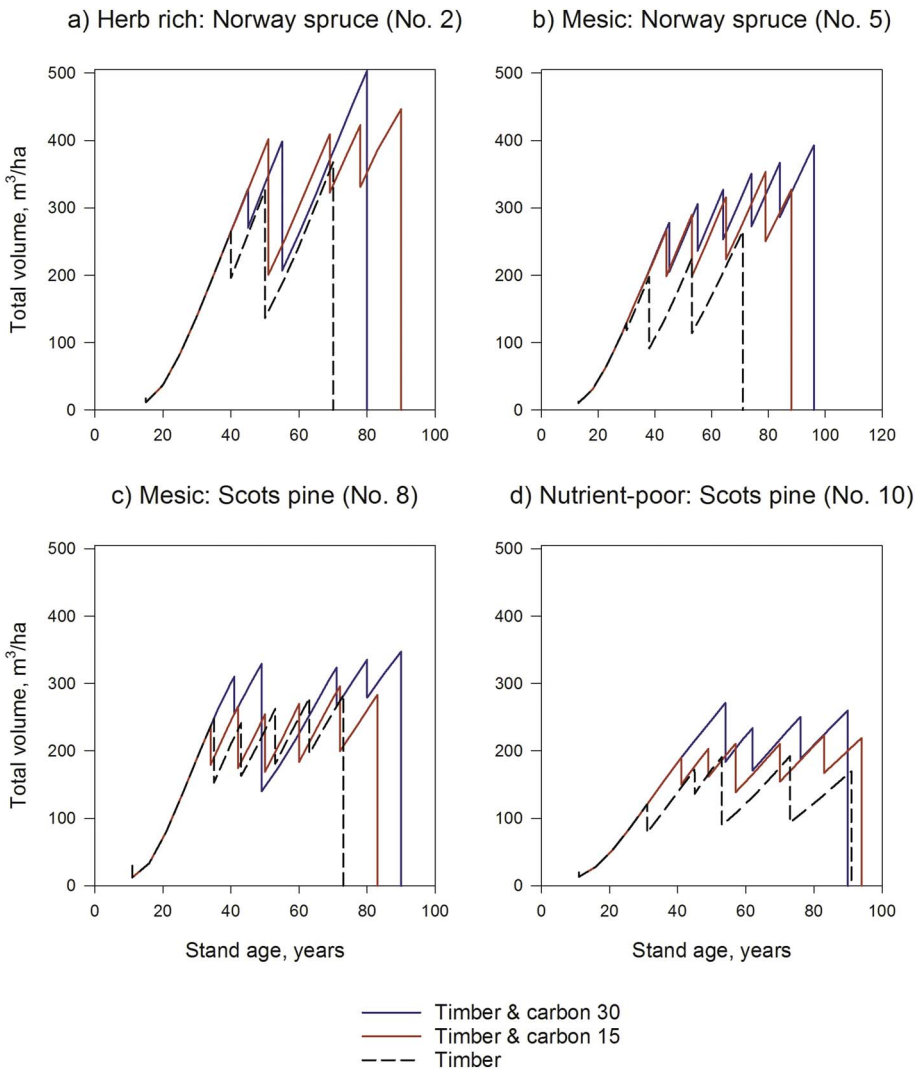
a) Herb rich: Norway spruce (No. 2)
b) Mesic: Norway spruce (No. 5)
c) Mesic: Scots pine (No. 8)
d) Nutrient-poor: Scots pine (No. 10)
Total volume, m3/ha
Stand age, years
Timber & carbon 30
Timber & carbon 15
Timber

Fig. 1. Merchantable timber volumes obtained with different management regimes optimized for timber production (dashed line) or for joint production of timber and carbon sink with prices of 30€ (blue line) and 15€ per CO_2 tn (red line) under no additionality requirement, i.e. entire carbon stock of trees is credited for trading. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Regarding all studied stands the average rotations are 71 and 78 years for herb rich and mesic Norway spruce stands and 73 and 95 years for Scots pine stands in mesic and nutrient poor sites, respectively (for these stands, see Table A.1 for the rows where carbon price is zero). The number of thinnings varies from two to six reflecting the fact that there are also differences in the intensity of thinnings: a low post-harvest density reduces the frequency thinnings. The average number of thinnings is 2.7 and 4.0 for herb rich and mesic Norway spruce stands and 4.3 and 5.0 for Scots pine stands in mesic and nutrient poor sites, respectively.

As expected, the NPV varies considerably between stands reflecting soil fertility: the higher soil fertility, the higher NPV (Table 2). On average Norway spruce stands have a higher NPV than Scots pine stands despite mesic pine stands have a slightly higher mean annual increment (MAI) than mesic spruce stands. How about the carbon stock in the stands under the timber management regime? For Norway spruce the average carbon stock is169 tCO_2 in herb rich sites and 153 tCO_2 in mesic sites (Table 2). The difference is explained by the fact that herb rich Norway spruce stands are the most fertile ones the average MAI being 8.6 m^3/ha against 7.7 m^3/ha in mesic stands. The figures for Scots pine stands in mesic and nutrient poor sites are 147 tCO_2 and 121 tCO_2, respectively. This benchmark provides the relevant yardstick to assess our two cases of carbon policies.

3.2. Payments for carbon sequestration under no additionality requirement

Introducing carbon policies with carbon prices of €15 tCO_2^{-1} and €30 tCO_2^{-1} changes both the optimal rotation period as well as the number and intensity of thinnings, as illustrated by the red and blue lines in Fig. 1 (and numbers in Table A.1). For the herb rich spruce stand the optimal rotation period lengthens from 70 to 90 years when carbon price is €15 tCO_2^{-1}, but is 80 year for price €30 tCO_2^{-1}. Hence, we have a shorter rotation length for higher carbon price, although both rotation lengths are longer than in the benchmark. For the mesic Norway spruce stand, the optimal rotation ages increase with the carbon prices ending up to 88 and 96 years, respectively. The difference in rotation ages between herb rich and mesic Norway spruce stands is explained by changes in thinnings, as Fig. 1a and b reveal. In the highly fertile herb rich site thinnings are delayed but the number of thinnings is the same as in the benchmark except with carbon price of €15 tCO_2^{-1} there is one extra thinning. In the mesic Norway spruce stand, the number of thinnings is increased and the thinning intensity is decreased in response to the carbon policy. For the mesic Scot pine the rotation lengthens to 83 and 96 years with carbon prices of €15 tCO_2^{-1} and €30 tCO_2^{-1}, respectively. With former price this is caused by increased number of thinnigs and with the latter by delayed thinnings. For the nutrient poor Scots pine stand the rotation lengthens only slightly to

Table 2
Net present value, average timber harvests, and average carbon stock under no additionality requirement, i.e. entire carbon stock of trees is credited for trading. Average values and distribution of values for stand examined (three stands per site type simulated).

		Carbon price (€/tCO_2)		
		0	15	30
Net present value (€/ha)	Herb-rich: spruce	5743 (4682–6768)	6999 (5868–8143)	8539 (7255–9931)
	Mesic: spruce	5054 (4328–6495)	6359 (5552–7834)	7769 (6950–9299)
	Mesic: pine	4542 (3828–5028)	5769 (5125–6168)	7153 (6675–7668)
	Nutrient-poor: pine	2194 (1234–3133)	3041 (1880–4103)	4085 (2698–5332)
Average timber harvests (m^3/a/ha)[a]	Herb-rich: spruce	8.6 (7.8–9.2)	8.8 (8.0–9.2)	9.1 (8.2–9.8)
	Mesic: spruce	7.7 (6.8–9.4)	8.2 (7.4–9.6)	8.3 (7.5–9.8)
	Mesic: pine	7.8 (6.9–8.3)	7.8 (7.1–8.2)	7.6 (7.2–8.0)
	Nutrient-poor: pine	5.0 (4.2–5.9)	5.1 (4.3–6.0)	5.3 (4.4–6.3)
Average carbon stock (tCO_2)[a]	Herb-rich: spruce	169 (161–175)	220 (195–236)	237 (223–247)
	Mesic: spruce	153 (134–182)	193 (169–207)	208 (190–224)
	Mesic: pine	147 (144–153)	182 (170–192)	214 (203 – 231)
	Nutrient-poor: pine	121 (114–133)	144 (139–151)	159 (151–175)

[a] During the rotation period.

94 years with carbon prices of €15 tCO_2^{-1}, and the number of thinnings increases whereas thinning intensity decreases. In contrast, the rotation is a little bit shortening to 90 years with price of €30 tCO_2^{-1}, because there is a strong (23 years) delay in the first thinning.

Results of all 12 stands showed that the increase in the rotation length is largest at high fertility sites. The number and intensity of thinnings may, however, change in many ways. First thinning is delayed in the most of the studied stands; the intensity of thinning is reduced and the number of thinnings increases to an average of 4.6 and 4.8 depending on the carbon price. Consequently, the average timber volume over the rotation period increases. The carbon payment does not change the precommercial thinnings, since tending of sapling stands is done in the beginning of the simulation period or not at all, because tending costs increase strongly as the tree diameter increases.

The state of the initial stand plays important role and create interesting exceptions to average outcomes. For example, the number of thinnings (stands No. 6 and No. 12) and the rotation length (stands No. 4 and No. 10) do not increase in all stands. The effect of carbon price is not always similar in the examined stand either. The higher the carbon price the more carbon is obviously produced, but the outcome is obtained either keeping the total volume at a high level by modifying thinnings (stands No. 2, No. 6 and No. 10) or extending the final cutting age (especially, stand No. 7).

The carbon pricing has considerable impact on rents (i.e., on the NPV), average timber volumes and stored carbon on all studied forest types (Table 2). The carbon payment increases strongly the profitability of forest management: the NPV increases about 50–100% at €30 tCO_2^{-1} price level. The profitability increases inversely to the forest fertility, indicating that in relative terms the nutrient-poor sites benefit most from the carbon payments. The carbon payments increase the average timber output except the opposite occurs in mesic pine sites. However, in all forest types the average timber output in terms of saw logs increases. Obviously, the carbon payments increase also the average carbon stock. Considering all studied stands, the increase of the average carbon stock over the rotation period is about 37 tCO_2 (57 tCO_2) at €15 tCO_2^{-1} (€30 tCO_2^{-1}) price level relative to the case where carbon incentives are absent. The increase varies largely between the stands. The outcome is not a surprise, because the optimal rotations are also different. In addition, it is not just the level but also the timing of stored carbon that matters in the joint production.

3.3. Payments for carbon sequestration under additionality requirement

The impacts of the short-term carbon payment scheme on the four stands in the presence of additionality (Fig. 2) is quite much the same as in the absence of additionality requirement (Fig. 1): the total volume and carbon stock are higher than in the absence of the carbon policies. There is a clear difference between Figs. 1 and 2, however, on herb rich and mesic Norway spruce stands, as the total volume is smaller when additionality is taken into account thanks to lower profitability of forestry.

Fig. 3 provides a deeper analysis of carbon evolvement during a rotation period for stand No 5 (black bars denoting price of €15 CO_2^{-1} and white bars the price of €30 CO_2^{-1}). Clearly, the carbon storage reaches a higher level than in the absence of carbon policies. The negative bars for certain years in Fig. 3 indicate that in some stands it is optimal to thin the trees and temporarily reduce the total volume below the reference timber management level. The key message of Fig. 3 is that the benefits from carbon trading are for the most part achieved by lengthen the rotation period.

Table 3 condenses the information on net present values, timber harvests and carbon stocks. The average profitability increases about 3% (11%) at €15 tCO_2^{-1} (€30 tCO_2^{-1}) price level compared to the case where only timber is produced; this is much less than in Table 2. The increase of the average carbon stock is about 33 tCO_2 (54 tCO_2) at €15 tCO_2^{-1} (€30 tCO_2^{-1}) price level compared to the pure timber management regime being slightly higher in the case without additionality requirement, that is, 37 tCO_2 (57 tCO_2), respectively.[5]

Using the results of optimization with the additionality requirement we conducted an additional analysis in which the marginal cost of carbon sequestration was determined for three selected stands representing different soil types and tree species (stands No 6, 9, and 12). Marginal cost with €15 tCO_2^{-1} carbon price was more or less similar, ranging from €1.77 to €1.95 regardless of tree species and soil type. With carbon price of €30 tCO_2^{-1} marginal cost was the highest with spruce (€4.57), the marginal cost with pine being considerably lower, €2.37–€2.65, depending on the soil type.

3.4. Break-even values for transaction costs

The short-term carbon payment scheme involves transaction costs. These are unknown, as the mechanism is not yet applied in practice. A priori, high transaction costs reduce the desirability of the system. To assess the feasibility of the mechanism, we estimated a break-even value for transaction costs, that is, a maximum level of transaction cost at which forest owner's net benefit of participation to the carbon trade is not negative.

[5] The effectivity of the short-term payment mechanism depended partly on the timber prices. For example, with regard to 33% increase in the stumpage prices, the average carbon stock reduced 7.0–13.3%. The NPV increased 29.1–36.2%, respectively. We conducted the sensitivity analysis with stands No 4–6 at €15 tCO_2^{-1} carbon price level.

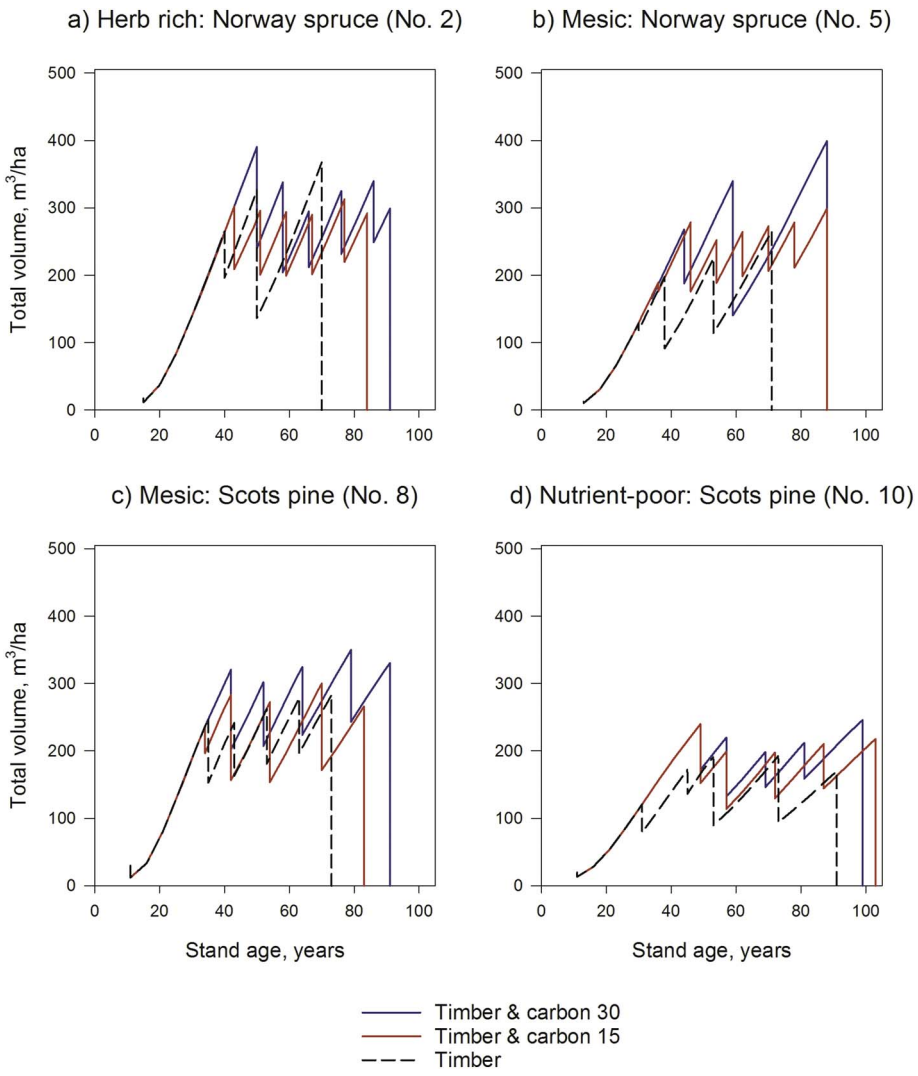
a) Herb rich: Norway spruce (No. 2)
b) Mesic: Norway spruce (No. 5)
c) Mesic: Scots pine (No. 8)
d) Nutrient-poor: Scots pine (No. 10)
Total volume, m3/ha
Stand age, years
Timber & carbon 30
Timber & carbon 15
Timber

Fig. 2. Merchantable timber volumes obtained with different management regimes optimized for timber production (dashed line) or for joint production of timber and carbon sink with prices of 30€ (blue line) and 15€ per CO_2 tn (red line) under additionality requirement, i.e. carbon stock of trees that is additional to that in the management optimized for timber production is credited for trading. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The maximum levels of transaction costs associated with the alternative carbon prices were calculated for the stand No 5 (cf. Fig. 3). With the additionality requirement the break-even values for the transaction costs were about €34 and €80 ha^{-1} for a contract at €15 and €30 $tCO_2{}^{-1}$ price levels. As anticipated, without the additionality requirement, the values were considerably higher, €62 and €139 ha^{-1}, respectively.[6]

3.5. Impacts of carbon payments at aggregate level: An illustration

This far our analysis has focused on stand-level only. Carbon payment mechanism is, however, motivated by the climate mitigation policies. Therefore, it is interesting to evaluate how beneficial the proposed short-term carbon payment scheme is at a regional level, that is, at landscape level. To answer this question we calculated the CO_2 reduction potential of forests in Southern Finland. The results in Table 4 clearly show that, in the long term, the short-term carbon payment mechanism can have a significant impact on climate change mitigation at national level in Finland. Calculating first the difference in average carbon stock between benchmark and climate-smart management using Table 3 and multiplying the difference with the two carbon prices reveals that the unit costs of potential carbon reduction varies between 8.0 and 53.2 euros per hectare for the considered forest types. Assuming then, for example, that one million hectares covering 11.5% of forestry land area are enrolled to the scheme in the southern Finland with carbon price €15 $CO_2{}^{-1}$ and that payments are distributed over the forest types following their existing shares of land areas, about 15 million euros would be spent annually for carbon payments and the reduction of annual CO_2 emission would be about 34.1 million ton. At €30 $tCO_2{}^{-1}$ price level with the same budget, the impact is smaller, 17.1 million CO_2 ton, as the costs are larger and the enrolled area is smaller, respectively.

4. Discussion and conclusions

We introduced and examined how a short-term carbon subsidy scheme promotes carbon sequestration in boreal forests involving long rotation periods. We allowed for alternative initial states of stands and allowed landowners to optimize over a wide range of management variables including rotation length and the number, timing, type, and

[6] The transaction costs of the short-term carbon payment mechanism are unknown. However, regarding a similar contract-based payment mechanism used to temporarily conserve private owned forests in Finland, Juutinen et al. (2013) estimated that landowners' transaction costs varied from €2 to €78 ha^{-1} depending on the size of the stand: the smallest stands had the highest transaction costs and vice versa.

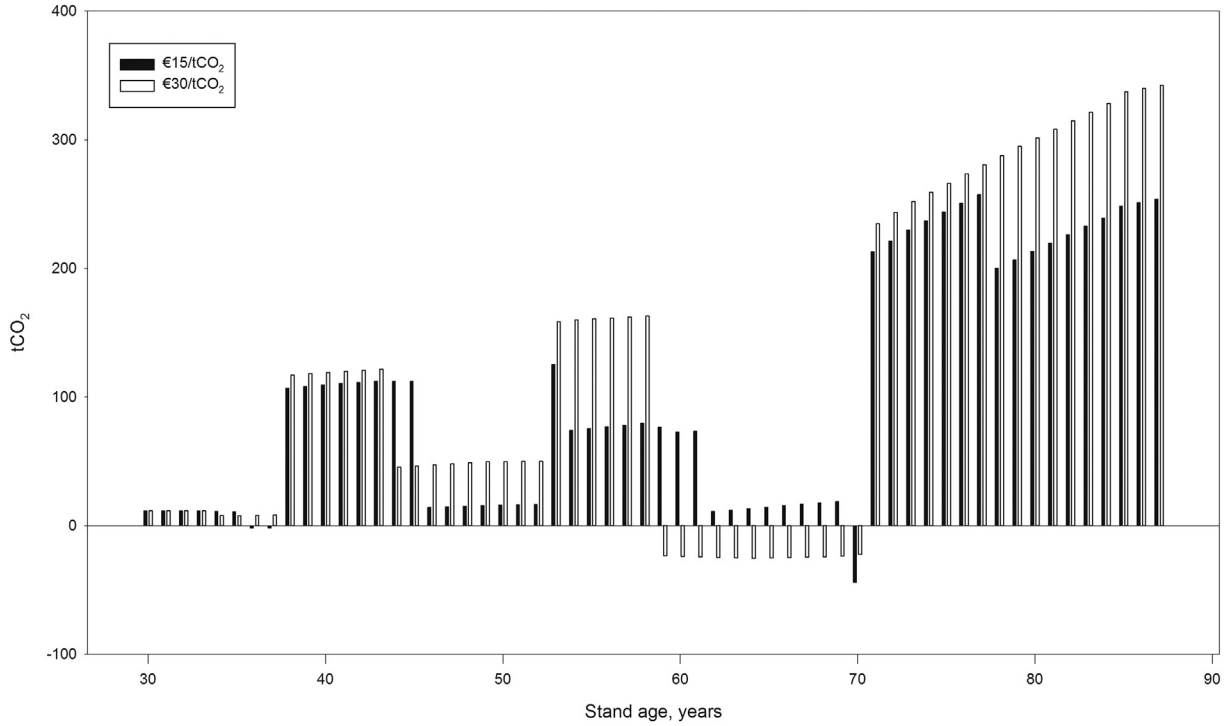

Fig. 3. Additional carbon under additionality requirement (stand No. 5). Negative tCO_2 values mean that carbon storage is below the reference timber management level (there are no penalties for the landowner in this case).

intensity of thinning.

We found that the short-term carbon payment system affects conclusively the optimal stand management and thinning strategy. This outcome is in line with the results of previous studies (e.g., Pohjola and Valsta, 2007; Niinimäki et al., 2013; Pihlainen et al., 2014). However, in contrast to the previous studies, the optimal management regimes turned out to be stand-specific to a large extent, i.e., optimal thinning regime and length of the rotation varied according to initial stand. This means that the traditional steady-state results may not provide enough guidance to shorter term climate policies in forestry. Landowners' short-term adaptation to carbon policies serves a study of its own.

The carbon payment tends to increase the optimal rotation period. In Norway spruce stands, the increase is the highest (even 25 years) but in some Scot pine stands especially on the least fertile sites the change is negligible. Furthermore, a higher price of carbon does not always increase the rotation length. Both results mark deviations from what previous literature found. While Pohjola and Valsta (2007) obtained similar results for Norway spruce, Niinimäki et al. (2013) suggested that in Norway spruce stands changing thinning strategies and postponing thinnings are at least as important as lengthening the rotation period. Most interestingly, in Pihlainen et al. (2014) the optimal solution for Scots pine stands consists of lengthening the rotations and in contrast to our study they concluded that the effect was strongest on the least fertile sites. Finally, unlike us, Niinimäki et al. (2013) and Pihlainen et al. (2014) found that carbon price always increases the rotation length.

Table 3
Net present value, average timber harvests, and average carbon stock under additionality requirement, i.e. carbon stock of trees that is additional to that in the management optimized for timber production is credited for trading. Average values and distribution of values for stand examined (three stands per site type simulated).

		Carbon price (€/tCO_2)		
		0	15	30
Net present value (€/ha)	Herb-rich: spruce	5743 (4682–6768)	5833 (4805–6880)	6181 (5180–7146)
	Mesic: spruce	5054 (4328–6495)	5255 (4505–6582)	5641 (5328–6737)
	Mesic: pine	4542 (3828–5028)	4651 (3948–5196)	5104 (4603–5651)
	Nutrient-poor: pine	2194 (1234–3133)	2266 (1295–3148)	2421 (1400–3318)
Average timber harvests (m^3/a/ha)[a]	Herb-rich: spruce	8.6 (7.8–9.2)	8.9 (8.0–10.0)	9.0 (8.4–9.6)
	Mesic: spruce	7.7 (6.8–9.4)	8.0 (7.0–9.5)	8.3 (7.6–9.8)
	Mesic: pine	7.8 (6.9–8.3)	7.9 (7.1–8.6)	7.8 (7.1–8.4)
	Nutrient-poor: pine	5.0 (4.2–5.9)	5.1 (4.4–6.0)	5.1 (4.4–5.8)
Average carbon stock (tCO_2)[a]	Herb-rich: spruce	169 (161–175)	220 (206–247)	229 (217–246)
	Mesic: spruce	153 (134–182)	180 (145–205)	213 (193–246)
	Mesic: pine	147 (144–153)	182 (168–194)	210 (195–222)
	Nutrient-poor: pine	121 (114–133)	139 (130–149)	153 (146–161)

[a] During the rotation period.

Table 4
Impacts of the short-term carbon payment scheme calculated for an area that represents forestry land in Southern Finland.

Forest type	Land share[a], %	Unit costs, €/ha/a		€15/tCO$_2$			€30/tCO$_2$		
		€15/tCO$_2$	€30/tCO$_2$	Targeted area, 1000 ha	Total costs, million €	CO$_2$, million tonnes	Targeted area, 1000 ha	Total costs, million €	CO$_2$, million tonnes
Herb-rich: spruce	28.5	22.6	53.2	285	6.4	14.5	89	4.8	5.4
Mesic: spruce	18.3	12.0	53.2	183	2.2	4.9	57	3.1	3.4
Mesic: pine	29.7	15.5	55.9	297	4.6	10.4	93	5.2	5.9
Nutrient-poor: pine	23.5	8.0	28.4	235	1.9	4.2	74	2.1	2.4
Total	100.0			1000	15.1	34.1	314	15.1	17.1

[a] Source: Anonymous, 2014.

One possible explanation for these contrasting results may be that Pihlainen et al. (2014) used a process-based model, but we used statistical empirical model just like Pohjola and Valsta (2007). There are also differences regarding the details in the economic setup (e.g., stumpage prices vs. road-side prices) between the studies, but most importantly our analysis focuses on the change in forest management of initial stands. Despite these differences, a robust result in all studies is that carbon pricing increases forest rents most at the poor sites (cf., Pihlainen et al., 2014).

The additionality requirement did not alter much the optimal management regime, but it reduced strongly the profitability of forest management in comparison to case where entire carbon stock of trees was credited. Including transaction costs would further reduce the carbon revenue to landowners (Cacho et al., 2013). This may restrict the applicability of the short-term mechanism in boreal forest to the cases of high carbon prices only, in particular, if the policy would be implemented with the additionality requirement. Our results demonstrated that, with the additionality requirement, relatively small transaction costs would make it clear that participation in the system that applies one-year contracts would not be profitable for the landowner. It is also worth pointing out that depending on the rules and institutional setting, uncertainty and asymmetric information may play a role. This holds true especially when additionality of carbon sequestration is required. The landowner knows the benchmark, while the buyer does not. Thus, when the benchmark is misreported (or alternatively miscalculated) the landowner sells more sequestration than actually takes place. The outcome is that carbon sequestration is lower than calculated and the costs of sequestration for the buyer are higher.

Short-term mechanism is, however, very efficient in inviting mature stands to carbon markets, because increasing the rotation length would be inexpensive way to capture revenue from carbon market. This ability to invite mature stands in carbon program is perhaps one the most important features of the short-term payment mechanism. In the long-term purchase approach mature stands are likely not offered into the carbon payment scheme, because final harvest will lead to a tax penalty. In addition, our results showed that the marginal costs of additional carbon were quite low varying from €1.8 to €4.6 at the considered carbon price levels, which is in line with previous findings (Pihlainen et al., 2014). This further indicates that the short-term payment mechanism can be considered as a cost-efficient option for climate change mitigation (cf., Ekholm, 2010).

The administrative details of the short-term payment mechanism would have to be designed in such a way that the transaction costs are not overwhelming. Therefore, a voluntary trading of carbon credits can only be based on an effective procedure on determining the carbon sequestrated in biomass, verification mechanism and a flexibly system by which credits can be sold to potential buyers. Example of such a system can be found in the New Zealand Emissions Trading Scheme (Adams and Turner, 2012). Our case differs from that scheme in one important respect: as a short term instrument, calculation of carbon sequestrated and verification of credits may be more frequent. In New Zealand ETS biomass is assessed roughly every 5 years, which could provide a model for short-term credits, as well. Carbon calculation could be based on modeling, which requires stand information as initial data input. Verification system would be on authorities and perhaps could follow the typical EU procedures followed for instance in the case of CAP measures. Once the system has been installed, it is our understanding that variable costs will be positive and moderate.

Turning to climate and environmental performance of the carbon payment instrument, we realize the boreal forests have a large potential to sequester carbon. For example, on a regional scale 34 million ton of CO_2 can be annually sequestrated with a cost of 15 million euros if short-term payment mechanism is applied on approximately 10% of forest area in southern Finland with carbon price €15 CO_2^{-1}. Under climate policies a stand contain 30 tons more carbon dioxide than in its absence. This impact can be achieved with relatively modest carbon payments. The illustrated reduction is impressive given that the annual CO_2 equivalent emissions in Finland are currently about 60 million ton (excluding the LULUCF sector, which is a sink) (http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php). The calculated carbon sequestration potential can be achieved only after the carbon payment scheme has been operational for several years or decades, as it will take time until the impacts of changed management practices will be fully realized. Interestingly, also timber output increases providing increased timber supply to forest industry. What is more, lengthened rotation ages and larger timber volumes in stands promote biodiversity as well (Juutinen et al., 2014), which is an important co-benefit of carbon policies (Matthies et al., 2016).

To conclude we emphasize that the short-term carbon rental policy would increase the profitability of forestry when applied in practice. Therefore, the policy could generate unwanted side-effects. In particular, it could increase afforestation, in which case agricultural land would be assigned to forestry in Finland. Pihlainen et al. (2014) have showed that at current agricultural land prices the afforestation due a carbon subsidy policy is not profitable in Finland. The carbon subsidy policy could, however, change the marginal value of agricultural land as well as timber price due the reallocation of land between agriculture and forestry. Anyway, in the carbon payment model, entry increases carbon and thereby climate benefits, unlike in a pollution model where entry increases emissions.

Appendix A. Appendix

Table A.1
Results of carbon trading without additionality requirement, i.e. entire carbon stock of trees is credited.

Stand	Carbon price €/tCO$_2$	Pre-commercial thinning[a]	Years of thinnings[b]	Time for final cutting[b] [removal, m^3/ha]	MAI[c]	Average storage, tCO$_2$	NPV, €/ha
Herb-rich (Oxalis-Myrtillus)/Norway spruce							
1	0	3500/1700 (10)	36 [99.1], 45 [89.1], 54 [88.0], 64 [94.7]	73 [297.4]	9.2 [7.2]	172	9136
1	15	3500/1700 (10)	38 [79.6], 46 [86.4], 54 [74.5], 62 [75.6], 70 [74.2], 78 [71.9]	87 [370.0]	9.6 [8.0]	236	10,992
1	30	3500/1700 (10)	41 [95.0], 49 [69.3], 57 [77.2], 66 [88.4], 75 [88.0], 85 [94.9]	92 [391.8]	9.8 [8.4]	241	13,405
2	0	3700/1700 (15)	40 [67.1], 50 [187.6]	70 [362.2]	8.8 [6.9]	175	9065
2	15	3700/1700 (15)	51 [201.0], 69 [83.1], 78 [88.6]	90 [408.9]	8.7 [7.4]	230	10,956
2	30	3700/1700 (15)	45 [56.1], 55 [189.8]	80 [496.9]	9.3 [7.6]	247	13,220
3	0	4770/1700 (16)	40 [80.8], 50 [131.0]	70 [330.8]	7.8 [5.6]	161	7567
3	15	4770/1700 (16)	41 [65.5], 49 [68.0], 57 [119.7], 69 [114.3], 84 [121.4]	91 [237.8]	8.0 [6.3]	195	9483
3	30	4770/1700 (16)	46 [62.0], 54 [130.8], 65 [71.3], 75 [80.7], 85 [80.6]	94 [348.0]	8.2 [6.7]	223	11,725
Mesic soil type (Myrtillus)/Norway spruce							
4	0	4040 NO	26 [37.8], 35 [70.1], 44 [89.5], 54 [101.7], 64 [107.0], 74 [114.1]	90 [328.1]	9.4 [7.1]	182	10,496
4	15	4040 NO	34 [52.7], 42 [78.4], 50 [83.9], 58 [88.2], 67 [93.8], 76 [97.0]	89 [356.6]	9.6 [7.2]	207	12,660
4	30	4040 NO	34 [41.8], 42 [79.1], 50 [77.2], 59 [92.1], 68 [91.7], 78 [99.0]	93 [430.7]	9.8 [7.7]	224	15,028
5	0	3690/1700 (13)	38 [107.1], 53 [114.2]	71 [260.4]	6.8 [4.8]	134	6392
5	15	3690/1700 (13)	44 [66.7], 53 [90.5], 65 [91.1], 79 [102.3]	88 [320.8]	7.6 [6.0]	202	8200
5	30	3690/1700 (13)	45 [58.4], 55 [68.3], 64 [72.8], 74 [77.6], 84 [80.1]	96 [385.8]	7.7 [6.4]	210	10,426
6	0	3500/1700 (10)	39 [70.7], 47 [54.9], 55 [61.1], 63 [59.2]	72 [259.7]	7.0 [4.9]	142	5856
6	15	3500/1700 (10)	49 [152.3], 64 [109.3], 79 [114.9]	94 [319.1]	7.4 [6.1]	169	7681
6	30	3500/1700 (10)	38 [36.8], 47 [49.3], 56 [65.3], 65 [66.8], 74 [67.3], 84 [74.2]	92 [333.9]	7.5 [6.1]	190	9381
Mesic soil type (Myrtillus)/Scots pine							
7	0	3170 NO	29 [74.6], 39 [111.2], 49 [73.2], 59 [79.1]	70 [236.2]	8.2 [4.3]	145	6994
7	15	3170 NO	39 [69.9], 49 [176.6], 67 [89.3]	76 [290.2]	8.2 [5.0]	192	8580
7	30	3170 NO	42 [58.4], 50 [161.1], 73 [120.8]	90 [374.8]	8.0 [5.3]	231	10,666
8	0	3590/1900 (11)	35 [82.7], 43 [78.0], 53 [81.0], 63 [81.9]	73 [278.5]	8.3 [5.0]	153	6634
8	15	3590/1900 (11)	34 [48.4], 42 [90.5], 50 [85.0], 60 [86.0], 72 [96.0]	83 [277.9]	8.2 [5.4]	170	8364
8	30	3590/1900 (11)	41 [54.2], 49 [188.0], 71 [57.3], 80 [56.1]	90 [341.1]	7.7 [5.4]	206	9898
9	0	4000 NO	22 [40.9], 30 [57.6], 40 [60.4], 50 [67.6], 64 [76.4]	75 [211.4]	6.9 [3.5]	144	5486
9	15	4000 NO	30 [53.9], 40 [48.3], 48 [51.4], 58 [58.2], 68 [61.1]	84 [326.5]	7.1 [4.1]	182	7346
9	30	4000 NO	32 [38.8], 40 [51.3], 48 [46.3], 57 [54.2], 66 [53.9], 75 [51.3], 85 [53.5]	90 [301.4]	7.2 [4.1]	203	9568

Nutrient-poor type (Vaccinium)/Scots pine							
10	0	2990/1900 (11)	31 [39.8], 45 [31.0], 53 [100.1], 73 [98.1]	91 [166.0]	4.8 [2.8]	117	3083
10	15	2990/1900 (11)	41 [38.9], 49 [40.9], 57 [71.1], 70 [55.7], 83 [55.2]	94 [213.6]	5.1 [3.1]	143	4368
10	30	2990/1900 (11)	54 [85.1], 62 [62.5], 76 [62.3]	90 [255.2]	5.2 [3.1]	153	5875
11	0	2790/1900 (11)	36 [53.7], 44 [70.6], 54 [57.3], 64 [59.8], 74 [56.7], 86 [60.7]	94 [199.9]	5.9 [3.8]	133	4358
11	15	2790/1900 (11)	39 [55.4], 47 [89.1], 55 [48.5], 63 [44.8], 71 [44.6], 79 [41.2], 87 [38.9]	95 [211.4]	6.0 [3.8]	151	5707
11	30	2790/1900 (11)	45 [78.8], 53 [53.7], 62 [54.4], 70 [47.4], 79 [50.1], 89 [51.8]	103 [295.4]	6.3 [4.1]	175	7416
12	0	6200/1900 (15)	45 [36.1], 54 [31.5], 62 [74.7], 75 [59.3], 90 [61.2]	99 [160.9]	4.2 [2.4]	114	1935
12	15	6200/1900 (15)	63 [73.5], 71 [80.1], 90 [86.1]	103 [206.9]	4.3 [2.6]	139	2948
12	30	6200/1900 (15)	61 [80.9], 71 [41.9], 81 [44.8], 91 [45.0]	105 [254.1]	4.4 [2.6]	151	4231

[a] Number of stems before tending/after tending (timing, yrs), NO denotes that tending was not executed.
[b] Removals (m^3/ha) are in the parentheses.
[c] MAI for sow logs in the parenthesis.

Table A.2
Results of carbon trading with additionality requirement, i.e. carbon stock of trees that is additional to that in the management optimized for timber production is credited.

Stand	Carbon price €/tCO_2	Pre-commercial thinning[a]	Years of thinnings[b]	Time for final cutting[b]	MAI[c]	Average storage, tCO_2	NPV, €/ha
herb-rich (Oxalis-Myrtillus)/Norway spruce							
1	0	3500/1700 (10)	36 [99.1], 45 [89.1], 54 [88.0], 64 [94.7]	73 [297.4]	9.2 [7.2]	172	9136
1	15	3500/1700 (10)	38 [71.5], 47 [76.0], 56 [85.8], 65 [86.2], 75 [95.9], 85 [93.6]	90 [395.8]	10.0 [8.6]	247	9287
1	30	3500/1700 (10)	45 [136.5], 56 [120.9], 71 [137.3]	90 [470.1]	9.6 [8.2]	246	9646
2	0	3700/1700 (15)	40 [67.1], 50 [187.6]	70 [362.2]	8.8 [6.9]	175	9065
2	15	3700/1700 (15)	43 [77.4], 51 [93.8], 59 [93.6], 67 [87.5], 77 [92.3]	84 [286.4]	8.7 [7.1]	207	9121
2	30	3700/1700 (15)	50 [130.0], 58 [132.1], 66 [81.9], 76 [92.3], 86 [90.5]	91 [293.2]	9.0 [7.7]	224	9750
3	0	4770/1700 (16)	40 [80.8], 50 [131.0]	70 [330.8]	7.8 [5.6]	161	7567
3	15	4770/1700 (16)	40 [117.1], 53 [38.8], 61 [64.2], 69 [63.3]	82 [376.7]	8.0 [6.1]	206	7765
3	30	4770/1700 (16)	47 [100.1], 56 [88.5], 66 [86.8], 77 [96.2]	96 [433.0]	8.4 [6.9]	217	8372
Mesic soil type (Myrtillus)/Norway spruce							
4	0	4040 NO	26 [37.8], 35 [70.1], 44 [89.5], 54 [101.7], 64 [107.0], 74 [114.1]	90 [328.1]	9.4 [7.1]	183	10,496
4	15	4040 NO	34 [74.0], 43 [81.7], 52 [94.7], 61 [94.3], 71 [102.9], 82 [107.3]	92 [321.5]	9.5 [7.2]	205	10,637
4	30	4040 NO	43 [85.4], 52 [83.7], 61 [88.9], 70 [90.9], 80 [99.4]	93 [462.7]	9.8 [8.0]	246	10,888
5	0	3690/1700 (13)	38 [107.1], 53 [114.2]	71 [260.4]	6.8 [4.8]	134	6392
5	15	3690/1700 (13)	46 [101.0], 54 [72.7], 62 [65.2], 70 [84.4], 78 [66.7]	88 [293.3]	7.6 [5.8]	190	6909
5	30	3690/1700 (13)	44 [81.2], 59 [197.2]	88 [393.2]	7.6 [5.9]	201	7487

6	0	3500/1700 (10)	39 [70.7], 47 [54.9], 55 [61.1], 63 [59.2]	72 [259.7]	7.0 [4.9]	142	5856
6	15	3500/1700 (10)	33 [30.5], 41 [79.0], 54 [124.1], 73 [136.1]	93 [279.8]	7.0 [5.5]	145	6081
6	30	3500/1700 (10)	40 [38.6], 49 [65.4], 58 [69.2], 68 [74.8], 78 [78.2], 88 [79.7]	94 [310.4]	7.6 [6.2]	193	6558
Mesic soil type (Myrtillus)/Scots pine							
7	0	3170 NO	29 [74.6], 39 [111.2], 49 [73.2], 59 [79.1]	70 [236.2]	8.2 [4.3]	145	6994
7	15	3170 NO	31 [35.8], 39 [82.5], 49 [88.4], 58 [74.4]	74 [352.8]	8.6 [5.0]	185	7227
7	30	3170 NO	39 [68.9], 49 [78.7], 58 [77.4], 70 [83.1]	82 [384.5]	8.4 [5.4]	215	7861
8	0	3590/1900 (11)	35 [82.7], 43 [78.0], 53 [81.0], 63 [81.9]	73 [278.5]	8.3 [5.0]	153	6634
8	15	3590/1900 (11)	34 [38.1], 42 [120.7], 54 [117.9], 70 [128.0]	83 [261.4]	8.0 [5.3]	168	6690
8	30	3590/1900 (11)	42 [104.9], 52 [94.4], 64 [99.9], 79 [106.1]	91 [325.0]	8.0 [5.7]	195	7034
9	0	4000 NO	40 [59.3], 48 [56.5], 56 [45.3], 64 [44.6], 73 [40.6], 82 [46.3]	75 [211.4]	6.9 [3.5]	144	5486
9	15	4000 NO	31 [39.8], 45 [31.0], 53 [100.1], 73 [98.1]	87 [320.7]	7.1 [4.1]	194	5659
9	30	4000 NO	50 [84.8], 58 [73.9], 69 [63.8], 85 [68.6]	91 [340.9]	7.1 [4.3]	222	6597
Nutrient-poor type (Vaccinium)/Scots pine							
10	0	2990/1900 (11)	31 [39.8], 45 [31.0], 53 [100.1], 73 [98.1]	91 [166.0]	4.8 [2.8]	117	3083
10	15	2990/1900 (11)	49 [81.5], 57 [84.3], 72 [67.6], 87 [65.6]	103 [213.7]	5.0 [3.2]	137	3278
10	30	2990/1900 (11)	49 [62.4], 57 [86.8], 69 [51.8], 81 [52.6]	99 [242.3]	5.0 [3.2]	146	3541
11	0	2790/1900 (11)	36 [53.7], 44 [70.6], 54 [57.3], 64 [59.8], 74 [56.7], 86 [60.7]	94 [199.9]	5.9 [3.8]	133	4358
11	15	2790/1900 (11)	42 [50.5], 50 [102.0], 58 [74.5], 72 [77.6], 87 [82.4]	94 [176.2]	6.0 [3.8]	149	4378
11	30	2790/1900 (11)	49 [94.4], 57 [114.4], 69 [60.9], 81 [60.6], 94 [59.7]	101 [194.0]	5.8 [3.9]	152	4615
12	0	6200/1900 (15)	45 [36.1], 54 [31.5], 62 [74.7], 75 [59.3], 90 [61.2]	99 [160.9]	4.2 [2.4]	114	1935
12	15	6200/1900 (15)	52 [35.9], 62 [36.4], 70 [102.4], 90 [84.8]	104 [194.4]	4.4 [2.6]	130	2031
12	30	6200/1900 (15)	67 [87.7], 75 [42.1], 83 [38.1], 91 [35.3]	104 [255.0]	4.4 [2.6]	161	2196

[a] Number of stems before tending/after tending (timing, yrs), NO denotes that tending was not executed.
[b] Removals (m^3/ha) are in the parentheses.
[c] MAI for sow logs in the parenthesis.

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2018.02.005.

References

Adams, T., Turner, J., 2012. An investigation into the effects of an emission trading scheme on forest management and land use in New Zealand. Forest Policy Econ. 15, 78–90.

Ahtikoski, A., Salminen, H., Hökkä, H., Kojola, S., Penttilä, T., 2012. Optimising stand management on peatlands: the case of northern Finland. Can. J. For. Res. 42, 247–259.

Ahtikoski, A., Salminen, H., Ojansuu, R., Hynynen, J., Kärkkäinen, K., Haapanen, M., 2013. Optimizing stand management involving the effect of genetic gain: preliminary results for Scots pine in Finland. Can. J. For. Res. 43, 1–7.

Anonymous, 2003. LUOTI maastotyöohje. Metsäntutkimuslaitos, tutkimusmetsäpalvelut. Metsäntutkimuslaitoksen tutkimusalueiden kuvioittaisen inventoinnin maastotyöohje. Moniste. 53p. [Practical guide for field inventories at stand level, User's manual with 53 pages, Finnish Forest Research Institute] [In Finnish].

Anonymous, 2006. Solmun maastokäyttöopas. Metsätalouden kehittämiskeskus Tapio. Metsäkustannus Oy. 82 p. [Field guide for using SOLMU system, User's manual with 82 pages, Forest Development Centre Tapio] [In Finnish].

Anonymous, 2014. Finnish Statistical Yearbook of Forestry, Official Statistics of Finland. Agriculture, Forestry and Fishery. Finnish Forest Research Institute, Tampere 2014. ISBN:978-951-40-2505-1 (pdf). 426 p.

Asente, P., Armstrong, W., 2012. Optimal forest harvest age considering carbon sequestration in multiple carbon pools: a comparative statics analysis. J. For. Econ. 18, 145–156.

Cacho, O., Lipper, L., Moss, J., 2013. Transaction costs of carbon offset projects: a comparative study. Ecol. Econ. 88, 232–243.

Cao, T., Hyytiäinen, K., Tahvonen, O., Valtsa, L., 2006. Effects of initial stand states on optimal thinning regime and rotation of *Picea abies* stands. Scand. J. For. Res. 21, 388–398.

Cao, T., Valsta, L., Mäkelä, A., 2010. A comparison of carbon assessment methods for optimizing timber production and carbon sequestration in scots pine stands. For. Ecol. Manag. 260, 1726–1734.
CEPA, 2014. Compliance offset protocol U.S. Forest projects. California Environmental Protection Agency. Air Resources Board November 14, 2014 (Available online). https://www.arb.ca.gov/regact/2014/capandtrade14/ctusforestprojectsprotocol.pdf, Accessed date: 11 December 2017.
Charbonneau, P., Knapp, B., 1995. A user's guide to PIKAIA 1.0, NCAR technical note 418+IA. In: High Altitude Observatory. National Center for Atmospheric Research, Boulder, Co.
Ekholm, T. 2010. Achieving cost efficiency with the 30% greenhouse gas emission reduction target of the EU. VTT working papers 149.
Galinato, G., Uchida, S., 2010. Evaluating temporal certified emission reductions in reforestation and afforestation programs. Environ. Resour. Econ. 46, 111–133.
Galinato, G., Uchida, S., 2011. The effect of temporary certified emission reductions on forest rotations and carbon supply. Can. J. Agric. Econ. 59, 145–164.
Galinato, G., Olanie, A., Uchida, S., Yoder, J., 2013. Long-term versus temporary certified emission reductions in forest carbon sequestration programs. Aust. J. Agric. Resour. Econ. 55, 537–559.
Goetz, R.-U., Hritonenko, N., Mur, R.J., Xabadia, A., Yatsenko, Y., 2010. Forest management and carbon sequestartion in sixe-strutured forests: the case of Pinus sylvestresis in Spain. For. Sci. 56, 242–256.
Hoen, H.F., Solberg, B., 1997. CO_2-taxing, timber rotations, and market implications. In: Critical review in environmental science and technology. 27. pp. 177–184 (Special).
Horne, P., 2006. Forest owners' acceptance of incentive based policy instruments in forest biodiversity conservation – a choice experiment based approach. Silva Fennica 40, 169–178.
Huuskonen, S., 2008. Nuorten männiköiden kehitys - taimikonhoito ja ensiharvennus [The development of young scots pine stands – precommercial and first commercial thinning]. 2008. University of Helsinki, Faculty of Agriculture and Forestry, Dissertationes Forestales, pp. 62 (Dr thesis. in Finnish).
Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen H., Haapala, P. 2002. Models for predicting stand development in MELA system. Metsäntutkimuslaitoksen tiedonantoja - the Finnish Forest research institute, research papers 835. 116 pp.
Hynynen, J., Ahtikoski, A., Siitonen, J., Sievänen, R., Liski, J., 2005. Applying the MOTTI simulator to analyse the effect of alternative management schedules on timber and non-timber production. For. Ecol. Manag. 207, 5–18.
Hynynen, J., Salminen, H., Huuskonen, S., Ahtikoski, A., Ojansuu, R., Siipilehto, J., Lehtonen, M., Rummukainen, A., Kojola, S., Eerikäinen, K., 2014. Scenario analysis for the biomass supply potential and the future development of Finnish Forest resources. In: Working papers of the Finnish Forest Research Institute 302, 106 pp. ISBN 978-951-40-2487-0 (PDF).
IPCC, 2006. Guidelines for National Greenhouse Gas Inventories, Volume 4 Agriculture, Forestry and Other Land Use. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.
Johansson, P.-O., Löfgren, K.-G., 1985. The Economics of Forestry & Natural Resources. Basil Blackwell, Oxford, UK 292 pp.
Juutinen, A., Mäntymaa, E., Ollikainen, M., 2013. Landowners' conservation motives and the size of information rents in environmental bidding systems. J. For. Econ. 19, 128–148.
Juutinen, A., Ollikainen, M., Mönkkönen, M., Reunanen, P., Tikkanen, O.-P., Kouki, J., 2014. Optimal contract length for biodiversity conservation under conservation budget constraint. Forest Policy Econ. 47, 14–24.
van Kooten, G.C., Binkey, C.S., Delcourt, G., 1995. Effect of carbon taxes and subsides on optimal forest rotation age and supply of carbon services. Am. J. Agric. Econ. 77, 365–374.
Latta, G., Adams, D., Alig, R., White, E., 2011. Simulated effects of mandatory versus voluntary participation in private forest carbon offset markets in the United States. J. For. Econ. 17, 127–141.
Lintunen, J., Laturi, J., Uusivuori, J., 2016. How should a forest carbon rent policy be implemented. Forest Policy Econ. 69, 31–39.
Liski, J., Pussinen, A., Pinqoud, K., Mäkipää, R., Karjalainen, T., 2001. Which rotation length is favourable to carbon sequestration? Can. J. For. Res. 31, 2004–2013.
Mäkelä, H., Hirvelä, H., Nuutinen, T., Kärkkäinen, L., 2011. Estimating forest data for analyses of forest production and utilization possibilities at local level by means of multi-source National Forest Inventory. For. Ecol. Manag. 262, 1345–1359.
Mäkinen, H., Hynynen, J., Isomäki, A., 2005. Intensive Management of Scots Pine Stands in southern Finland: first empirical results and simulated further development. For. Ecol. Manag. 215, 37–50.
Man, C., Lyons, K., Nelson, J., Bull, G., 2015. Cost to produce carbon credits by reducing the harvest level in British Columbia, Canada. Forest Policy Econ. 52, 9–17.
Markowski-Lindsay, M., Stevens, T., Kittredge, D.B., Butler, B.J., Catanzaro, P., Dickinson, B.J., 2011. Barriers to Massachusetts forest landowner participation in carbon markets. Ecol. Econ. 71, 180–190.
Matala, J., Hynynen, J., Miina, J., Ojansuu, R., Peltola, H., Sievänen, R., Väisänen, H., Kellomäki, S., 2003. Comparison of a physiological model and a statistical model for prediction of growth and yield in boreal forests. Ecol. Model. 161, 95–116.
Matthies, B., Kalliokoski, T., Eyvindson, K., Honkela, N., Hukkinen, J., Kuusinen, N., Räisänen, P., Valsta, L., 2016. Nudging service providers and assessing service tradeoffs to reduce the social inefficiencies of payments for ecosystem services schemes. Environ. Sci. Pol. 55, 228–237.
Metcalfe, T.S., Charbonneau, P., 2003. Stellar structure modeling using a parallel genetic algorithm for objective global optimization. J. Comput. Phys. 185, 176–193.
Moen, J., Rist, L., Bishop, K., Chapin, F.S., Ellison, D., Kuuluvainen, T., Petersson, H., Puettmann, K.J., Rayner, J., Warkentin, I.G., Bradshaw, C.J.A., 2014. Eye on the taiga: removing global policy impediments to safeguard the boreal forest. Conserv. Lett. 7, 408–418.
Nabuurs, G.-J., Delacote, P., Ellison, D., Hanewinkel, M., Lindner, M., Nesbit, M., Ollikainen, M., Savaresi, A., 2015. A new role for forests and the forest sector in the EU post-2020 climate targets. In: From Science to Policy 2. European Forest Institute.
Niinimäki, S., Tahvonen, O., Mäkelä, A., Linkosalo, T., 2013. On the economics on Norway spruce stands and carbon storage. Can. J. For. Res. 43, 637–648.
Olschewski, R., Benitez, P., 2010. Optimizing joint production of timber and carbon sequestration of afforestation projects. J. For. Econ. 16, 1–10.
Pihlainen, S., Tahvonen, O., Niinimäki, S., 2014. The economics of timber and bioenergy production and carbon storage in Scots pine stands. Can. J. For. Res. 44, 1091–1102.
Pohjola, J., Valsta, L., 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. Forest Pol. Econ. 9, 789–798.
Pukkala, T., 2011. Optimizing forest management in Finland with carbon subsides and taxes. Forest Policy Econ. 13, 425–434.
Salminen, H., Lehtonen, M., Hynynen, J., 2005. Reusing legacy FORTRAN in the MOTTI growth and yield simulator. Comput. Electron. Agric. 49, 103–113.
Statistics Finland, 2014. Consumer price index 2013, December. Appendix table 2. Cost-of living index 1951:10=100. Helsinki 14.1.2014.
Tahvonen, O., 1995. Net national emissions, CO_2 taxation and the role of forestry. Resour. Energy Econ. 17, 307–315.
Tahvonen, O., Pihlainen, S., Niinimäki, S., 2013. On the economics of optimal timber production in boreal scot pine stands. Can. J. For. Res. 43, 719–730.
Tol, R.S., 2005. The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energ Policy 33, 2064–2074.
Tol, R.S., 2011. The social cost of carbon. Ann. Rev. Resour. Econ. 3, 419–443.
Tonteri, T., Hotanen, J.P., Kuusipalo, J., 1990. The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. Vegetatio 87, 85–98.
UNFCCC, 2011. Report of the conference of the parties serving as the meeting of the parties to the Kyoto protocol on its sixth session, held in Cancun from 29 November to 10 December 2010 (Available online). http://unfccc.int/resource/docs/2010/cmp6/eng/12a01.pdf, Accessed date: 11 December 2017.
Venäläinen, A., Tuomenvirta, H., Pirinen, P., Drebs, A., 2005. A basic Finnish climate data set 1961-2000 – description and illustrations. In: Finnish Meteorological Institute, Reports No. 2005:5, pp. 1–27.